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Implicit Memory and Cognitive Aging

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Summary

It is well documented that explicit (declarative, conscious) memory declines in normal aging. Studies have shown a progressive reduction in this form of memory with age, and healthy older adults (typically aged 65+ years) usually perform worse than younger adults (typically aged 18-30 years) on laboratory tests of explicit memory such as recall and recognition. In contrast, it is less clear whether implicit (procedural, unconscious) memory declines or remains stable in normal aging. Implicit memory is evident when previous experiences affect (e.g., facilitate) performance on tasks that do not require conscious recollection of those experiences. This can manifest in rehearsed motor skills, such as playing a musical instrument, but is typically indexed in the laboratory by the greater ease with which previously studied information is processed relative to non-studied information (e.g., repetition priming). While a vast amount of research has accumulated to suggest that implicit memory remains relatively stable over the adult lifespan, and is similar in samples of young and older adults, other studies have in contrast revealed that implicit memory is subject to age-related decline. Improving methods for determining whether implicit memory declines or remains stable with age is an important goal for future research, as the issue not only has significant implications for an aging society regarding interventions likely to ameliorate the effects of age-related explicit memory decline, but can also inform our theoretical understanding of human memory systems.

***Keywords**:* cognitive aging; implicit memory; priming; explicit memory; memory systems

The age distribution of the global population is rapidly changing. The proportion of individuals over the age of 65 years reached 8.5% of the total population in 2015, is expected to increase by 236 million in the next ten years, and almost double to 1.6 billion between 2025 to 2050 (U.S. Census Bureau, 2015). In light of this there is great importance in studying age-related changes in cognition, particularly learning and memory. Memory can manifest itself in various different ways, from procedural skills to the ability to recall prior experiences, and although it is clear that the conscious recall of previously learned information declines with age, the effect of aging on implicit memory continues to be the subject of debate. This review draws together evidence from prominent historical and recent research on the effect of cognitive aging on implicit memory, and critically evaluates contrasting views about the preservation versus decline of this form of memory with age. The culmination is several recommendations for methodological improvement in future research, aimed at placing on a firmer footing the consensus view that there is a small decline in implicit memory with age.

Human long-term memory: Explicit versus implicit

Our understanding of *implicit memory* and its relationship with *explicit memory* has evolved over the past few decades. Implicit (sometimes called nondeclarative) memory has traditionally been considered one of two distinct forms of long-term memory, the other being explicit (sometimes called declarative) memory (e.g., Graf & Schacter, 1985, 1987). Explicit memory is the conscious retrieval of previously learned information or prior experiences, while implicit memory is evident when previous experiences affect (e.g., facilitate) performance on tasks that do not require conscious recollection of those experiences (Schacter, 1987). Explicit memory is measured using tasks that directly instruct participants to deliberately attempt to retrieve specific information from a prior study episode. For example, participants may be exposed to a series of items such as words or pictures of objects before being asked to recall as many as possible, or in the case of recognition to discriminate between previously studied and new items.

Implicit memory, on the other hand, is measured indirectly without reference to the prior study episode (Lewandowsky, Dunn, & Kirsner, 1989; Reder, 2014). It involves the comparison of performance in relation to previously studied and new items on a seemingly unrelated task, such as perceptual identification. In this task, participants are presented with words or objects very briefly or in a degraded form and are instructed to identify them (i.e., name them) as quickly as possible. Implicit memory is revealed by reduced identification latencies and/or greater accuracy associated with previously studied relative to new items. This is known as repetition priming (henceforth *priming*) and can be a very robust phenomenon: for instance, all 32 participants in a perceptual identification experiment by Berry, Shanks, Speekenbrink, and Henson (2012, Experiment 1) identified studied words faster than new ones.

The terms implicit memory and priming are often used interchangeably to refer to the effects of prior exposure to specific stimuli on performance on subsequent tests that do not require conscious recollection of those stimuli (Tulving & Schacter, 1990). Other commonly used implicit tasks are word-fragment and word-stem completion. In these tasks, following an initial phase in which a series of words are presented (e.g., HOUSE, TRUCK, GLASS, etc), participants are asked to complete word-fragments (e.g., H_ _ SE) or stems (e.g., HO_ _ _) with the first word that comes to mind. Priming is evident when the prior exposure increases the likelihood of using previously studied words as solutions (e.g., ‘HOUSE’ rather than a novel word such as ‘HORSE’ in the above example).

Explicit and implicit memory are believed by many to be driven by functionally independent memory systems (e.g., Gabrieli, 1998; 1999; Schacter, 1987; Schacter &

Tulving, 1994; Squire, 1994, 2004, 2009; Tulving & Schacter, 1990). Classic early studies that have been heavily cited as a key strand of evidence for this multiple-systems perspective reported spared priming in patients with amnesia despite severely impaired explicit memory (e.g., Graf, Squire, & Mandler, 1984; Hamann & Squire, 1997a, 1997b; Warrington & Weizkrantz, 1968; 1970; 1974). Although far less drastic, the explicit memory decline that occurs with age is similar to that observed in amnesia, so it comes as no surprise that there has been a determined effort to examine possible dissociations between explicit and implicit memory in aging. As will be reviewed in the section on *Normal aging and implicit memory*, a plethora of studies were published that largely concluded that implicit memory is preserved with age despite a decline in explicit memory (for earlier discussions see Fleischman, 2007; Fleischman & Gabrieli, 1998; Light, 1991; Light, Prull, La Voie, & Healy, 2000; Mitchell, 1989; Mitchell & Bruss, 2003; Ward, Berry, & Shanks, 2013b). In theoretical terms this has often been taken as evidence for multiple memory systems, but the picture is not straightforward as a growing body of evidence suggests that implicit memory may not be preserved with age. As will be elaborated in the section on *Theoretical implications*, an alternative view is that explicit and implicit memory are driven by a single system (e.g., Berry, Henson, & Shanks, 2006; Berry, Shanks, & Henson, 2008a; 2008b; Berry, Shanks, Speekenbrink, & Henson, 2012; Berry, Ward, & Shanks, 2017; Buchner & Wippich, 2000; Dunn, 2003; Nosofsky, Little, & James, 2012; Ward, Berry, & Shanks, 2013a; Ward et al., 2013b).

Memory in normal aging

This review is limited in focus to normal aging. Although dementia (e.g., Alzheimer's disease) and mild cognitive impairment are common, healthy older individuals without these pathologies also experience cognitive decline. Our brain capacity peaks at around the age of

25-30 years, prior to a gradual decline that becomes more pronounced from around 60 years of age (Dennis & Cabeza, 2008; Raz & Rodrigue, 2006). A prominent neuropathological feature of normal aging is marked shrinkage of neuronal tissue in the frontal lobes and hippocampal regions (e.g., Bartzokis et al, 2001; Jernigan et al., 2001; Pfefferbaum et al., 1998; Raz, 2000; Resnick et al., 2003). Associated changes in cognition include reductions in processing speed (the speed with which cognitive operations can be executed: Salthouse, 1978; 1980) and impaired executive function (including attention, inhibition, task switching, and monitoring, e.g., Salthouse, Atkinson, & Berish, 2003; Salthouse, Fristoe, McGuthry, & Hambrick, 1988), but perhaps the most well documented and extensively studied feature of cognitive aging is memory decline. As is reviewed in the following subsections, it is generally accepted that explicit memory declines with age, but there is disagreement as to whether implicit memory is also susceptible to age-related decline.

Explicit memory decline

Explicit memory function is thought to increase up to around the age of 25–30 years, after which time it begins to steadily decline (e.g., Nilsson, 2003). A progressive decline in later adulthood has been shown longitudinally. For example, Fleischman, Wilson, Gabrieli, Bienias, and Bennet (2004) reported declines over a four-year period in a sample of females with a mean age of 78.6 years on explicit tests involving immediate and delayed recall and recognition of stories, numbers and words (see also Christensen, Henderson, Griffiths, & Levings, 1997; Davis, Trussell, & Klebe, 2001; Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon, 1992). Additionally, there is vast evidence from cross-sectional studies that older adults (typically aged 65 years and over) perform worse than their younger counterparts (typically aged 18-30 years) on laboratory tests such as recall and recognition (e.g., Burke & Light 1981; Craik, 1994; Craik & Schloerscheidt, 2011; Howe; 1988; Hultsch

& Dixon 1990; Jelicic, Craik, & Moscovitch, 1996; Ward, 2018; Ward, de Mornay Davies, & Politimou, 2015; Ward, Maylor, Poirier, Korko, & Ruud, 2016). For detailed reviews of the decline of explicit memory with age see Kausler, 1994; Light et al. 2000; Spaan, Raaijmaker and Jonker, 2003.

These age-related changes in explicit memory have been linked to the aforementioned structural changes in the medial temporal lobe, particularly the hippocampus and entorhinal cortex (e.g., Geinisman, Detoledo-Morrell, Morrell, & Heller, 1995; Kordower et al., 2001; Raz, Rodrigue, Head, Kennedy, & Acker, 2004; Small, Nava, Perera, Kelapex, & Stern, 2000; Stoub et al., 2005). Shrinkage of white matter in these areas shows up as high signal intensity areas on MRI scans, referred to as white matter hyperintensities, and memory decline is correlated with the number of hyperintense regions (e.g., Au et al., 2006; de Groot et al., 2000; Smith et al., 2011). Moreover, the breakdown of myelin sheaths around neurons is thought to affect signal conduction, contributing to cognitive slowing, which may mediate explicit memory impairment. For example, cognitive slowing may constrain the encoding of new information to memory, may prevent new associations from being formed (MacKay & Burke, 1990), and also cause retrieval failures (Brown & Nix, 1996). Indeed, Salthouse (1985) found that performance on the Wechsler Digit Symbol Substitution Task (Wechsler, 1997), a standardised measure of processing speed, was significantly correlated with performance on explicit memory tasks such as free recall, spatial recall, and paired associate learning.

Failures of metamemory, the use of inappropriate encoding/retrieval strategies, and weakening of the senses involved in the intake of information (e.g., vision, hearing) may also contribute to explicit memory decline with age (for a thorough review see Light, 1991). It has also been suggested that memory traces are encoded in an increasingly shallow manner with age, and that older adults require greater environmental support (e.g., retrieval cues) in order to consciously access information stored in memory (e.g., Craik & Salthouse, 2008). Lastly, a reduction in inhibitory control processes with age means that older adults are particularly susceptible to intrusion from irrelevant information, and this may interfere with the memorial processing of relevant information (e.g., Hasher & Zacks, 1988; Zacks, Hasher, & Li, 2000).

It is noteworthy that the extent to which explicit memory is affected by aging varies depending upon the task used, and this may offer further clues as to the specific cognitive processes that are impaired. Namely, there appears to be a greater age-related deficit in recall than recognition. For example, Schugens, Daum, Spindler, and Birbaumer (1997) found age-related deficits in older compared to young adults on tasks measuring immediate and delayed verbal and visual recall, while age differences in recognition were not always reliable (see also Moscovitch & Winocur, 1992; Naveh-Benjamin & Craik, 1995). One reason may be that recall involves a particularly effortful and self-initiated search of memory, whereas recognition tasks provide greater environmental support in the form of retrieval cues (Craik & McDowd, 1987). The patterns could also reflect greater age-related reduction in the process of recollection compared to familiarity (e.g., Jennings & Jacoby, 1993; Light et al., 2000; Prull, Dawes, Martin, Rosenberg, & Light, 2006; Parks, DeCarli, Jacoby, & Yonelinas, 2010; Ward et al., 2016; Yonelinas, 2002). Recollection is the detailed conscious retrieval of some specific information, including the context in which it was studied, while familiarity is merely the feeling that some specific information has been encountered before, and a widely held view is that recognition can be based upon either process (e.g., Jacoby, 1991; Rotello, Macmillan, & Reeder, 2004; Wixted, 2007; Yonelinas, 2002; Yonelinas & Levy, 2002). That is, even in the absence of specific item recollection, recently studied items are associated with greater familiarity than new items, which can serve as a basis for accurate recognition.

Normal aging and implicit memory

In light of the clear deficit in explicit memory function with age, there has been a profound interest over the past few decades in establishing whether implicit memory is similarly or differentially affected. Many studies have concluded that implicit memory is preserved with age, and if true, this could have considerable theoretical and practical implications. For example, the preservation of implicit memory with age might open up significant opportunities to remediate decline in real-life demands, such as acquiring face-name associations or learning medication routines, and moreover if implicit memory is preserved in healthy older individuals but not those with Alzheimer's disease (see Fleischman, 2007, for a review), suitably designed implicit tasks might provide a valuable diagnostic tool (discussed further in the section on *Implications and future directions*). The picture, however, is not clear, as the literature is replete with contradictory findings.

Several longitudinal studies have reported that priming remains stable with age (Christensen et al., 1997; Davis, Cohen, Gandy, Colombo et al., 1990; Davis et al., 2001; Fleischman et al., 2004; Hultsch et al., 1992). Although most used relatively small numbers of participants and a single priming task, Fleischman et al. (2004) examined implicit memory in a large sample of females using a range of tasks designed to capture differences in conceptual, perceptual, production, and identification processes, namely, category-exemplar production, word-stem completion, word identification, and picture naming. Despite a clear reduction in explicit memory, priming remained stable across all tasks over the four-year period of the study.

Additionally, a number of cross sectional studies have reported statistically equivalent priming in young and older adults on tests of word-stem completion (e.g., Jelicic et al., 1996; Light & Singh, 1987, Experiments 1 and 2; Park & Shaw, 1992; Mitchell & Bruss, 2003; Spaan & Raaijmarkers, 2010), word-fragment completion (e.g., Light, Singh, & Capps, 1986;

Mitchell & Bruss, 2003), perceptual identification (word and picture) (e.g., Light, La Voie, Valencia-Laver, Albertson-Owens, & Mead, 1992; Light & Singh, 1987, Experiment 3; Russo & Parkin, 1993; Sullivan, Faust, & Balota, 1995; Wiggs, Weisberg, & Martin, 2006), object decision (e.g., Schacter, Cooper & Valdiserri, 1992; Soldan, Hilton, Cooper, & Stern, 2009; Gordon, Thomas, Soldan, & Stern, 2013), picture fragment identification (Mitchell & Bruss, 2003), picture naming (e.g., Mitchell, 1989; Mitchell, Brown, & Murphy, 1990; Mitchell & Bruss, 2003; Mitchell & Schmitt, 2006), lexical decision (e.g., Karavanidis, Andrews, Ward, & McConaghy, 1993; Moscovitch, 1982), homophone spelling (e.g., Howard, 1988, Experiments 2 and 3; Mitchell & Brown, 1990), category exemplar generation (e.g., Mitchell & Bruss, 2003), and associative priming (e.g., Howard, Heisey, & Shaw, 1986; Rabinowitz, 1986).

In contrast, a growing body of evidence suggests that priming is not stable with age. Reductions in priming have been reported on tests, of word-stem completion (e.g., Chiarello & Hoyer, 1988; Davis et al., 1990; Hultsch, Mason, & Small, 1991; Small, Hultsch, & Masson, 1995), unfamiliar word/object naming (e.g., Keane, Wong, & Verfaellie, 2004; Soldan et al., 2009; Wiggs & Martin, 1994), category exemplar generation (Stuart, Patel, & Bhagrath, 2010), category verification (Light, Prull, & Kennison, 2000, Experiment 2), perceptual identification (e.g., Abbenhuis, Raaijmakers, Raaijmakers, & Van Woerden 1990; Russo & Parkin, 1993; Ward, 2018; Ward et al., 2013a), and homophone priming (e.g., Davis et al. 1990; Howard, 1988; Experiment 1; Rose, Yesavage, Hill & Bower, 1986). The inconsistencies in the literature have greatly impeded a clear consensus around the effect of cognitive aging on implicit memory. To begin to evaluate what conclusions can reasonably be drawn at this time, it is necessary to look at possible reasons behind the discrepancies. These may include a range of methodological and measurement factors, including power and task reliability, processing characteristics, participant characteristics, and explicit contamination. These issues are considered in turn in the sections that follow.

Power and task reliability

Of the numerous published studies on the effect of age on implicit memory, sample sizes have varied considerably. Thus, statistical power to detect differences in task performance between young and older adults is likely to have varied between studies. This is problematic because if there is a genuine but small effect of age on implicit memory, in many cases it may have gone undetected (failure to reject a false null hypothesis). Indeed, of the studies that have reported no reliable age difference in priming between young and older adults, priming has usually been numerically lower in older than younger adults, and a meta-analysis by La Voie and Light (1994) uncovered a small but significant effect of age. Given the well-known limitations of concluding that an effect does not exist based on a null result, it is surprising that it has come to be so well accepted that implicit memory is spared with age.

However, statistical age differences in implicit memory have been reported in studies with as few as 11 participants (e.g., Abbenhuis et al., 1990), and increasing the sample size does not guarantee the emergence of a reliable age difference in priming: Park and Shaw (1992) reported a nonsignificant age difference in a study with over 140 participants per group. Thus, although there is no doubt that statistical power can affect outcomes, this alone cannot account for the discrepancies in the literature.

The power issue is exacerbated by the differential sensitivity of the various priming tasks that have been used to examine age effects. The ability to detect age differences in priming depends not only on the power of the experiment given the sample size, but also the reliability of the key dependent measures, yet only a handful of studies in the aging literature have considered this important issue (e.g., Buchner & Wippich, 2000; Hultsch, Masson, &

Small, 1991; Meier & Perrig, 2000; Mitchell & Bruss, 2003; Small, Hultsch, & Masson, 1995; Ward et al., 2013a). Comparisons are frequently made between recognition and word-stem completion tasks, yet Buchner and Wippich (2000) demonstrated that differences in the inherent reliability of these tasks can explain the age-differential patterns. Split-half correlations were used to objectively compute and compare the respective reliabilities of the two tasks, and word-stem completion was shown to be statistically less reliable than recognition (scores of .35 and .88 for word-stem completion and recognition, respectively, in Experiment 1). The split-half method involves examining the correlation between scores for one half of the test versus the other, such as odd and even trials. For a reliable task, scores will be strongly correlated. Buchner and Wippich argued that tasks such as word-stem completion are associated with high response variability, perhaps due to inconsistencies between participants in their interpretation of the task instructions, which contributes to noisy data from which it is difficult to statistically detect small but real age differences. That is, compared to a recognition task in which there is a clear and rigid goal to discriminate between previously studied and new items, the instruction to complete word stems with the first word that comes to mind is less stringent and allows a considerable amount of flexibility in terms of performance strategy. At variance with this proposal, however, Mitchell and Bruss (2003) reported a reliability score of .69 for word-stem completion, which was equivalent to explicit free recall. In their study, the split half method was used to examine reliability for five implicit tasks (category exemplar generation, word-stem and word-fragment completion, picture naming, and picture fragment identification) and the resulting scores ranged from .57 (picture fragment identification) to .78 (picture naming). If weak measure reliability masks a genuine decline in implicit memory with age, then a fundamental goal should be to develop or uncover implicit tasks with adequate reliability. Perceptual identification is one implicit task that, similarly to explicit tasks such as recognition, has a clear goal – to identify words or objects as quickly as possible. There are a limited variety of strategies that can be employed in perceptual identification, and moreover the speeded nature of the task means that there is very little time for participants to engage in any other strategy than to simply follow instructions to identify targets as quickly as possible. Perceptual identification should therefore be associated with greater reliability than implicit tasks with less stringent instructions. Indeed, Buchner and Wippich (2000) reported an instance in which a perceptual identification task had a reliability level greater than that of a word-stem completion task, and equivalent to an explicit recognition task. In contrast, the perceptual identification task used in Ward et al. (2013a), the continuous identification (CID) task (Figure 1), had lower reliability than a recognition task, but with adequate statistical power the study was still able to uncover a small but significant reduction in priming with age.

On the whole, given that many published studies may have been underpowered and/or used implicit tasks with low sensitivity to detect genuine but small age differences in priming, it cannot be concluded that implicit memory is completely unaffected by age. However, if there is a genuine effect of age on implicit memory, then it appears to be very small.

Processing and task characteristics

Just as different implicit tasks may be more or less sensitive to aging depending upon their reliability, age effects may differ across tasks depending on the specific cognitive processes that they engage (Fleischman & Gabrieli, 1998). A broad distinction has been made between *perceptual* and *conceptual* implicit tasks. Perceptual implicit tasks yield maximal priming when participants are engaged with the perceptual features (e.g., visual or auditory) of target items at study and test, and priming is reduced when there is a format change between items presented at study and test, such as from visual to auditory modality or from word to object (e.g., Roediger & McDermott, 1993). Common priming tasks that are considered to be largely perceptual include perceptual identification, word-fragment and word-stem completion, lexical decision, and solving anagrams. Conceptual priming tasks, on the other hand, yield greatest priming when participants are engaged with the conceptual features (i.e., content and meaning) of target items at study and test, and are unaffected by changes in the perceptual features of items between phases. Examples of conceptual implicit tests include word association, category exemplar generation, and fact completion.

It is generally agreed upon that the ability to engage in conceptual processing declines to a greater extent with age than perceptual processing (e.g., Rybash, 1996), so one may expect larger age effects on implicit tasks that draw upon conceptual processes than those that require perceptual processing (see Geraci & Hamilton, 2009; Roediger & Blaxton, 1987a, 1987b; Weldon, 1991). Evidence that aging selectively diminishes conceptual priming and leaves perceptual priming spared, however, is mixed. As outlined in the section on *Normal aging and implicit memory*, some studies have reported spared priming on perceptual implicit tasks such as word-stem completion and perceptual identification, while others have reported reduced priming in older compared to young adults on the same tasks. Moreover, some studies have reported age-invariant conceptual priming on tasks such as word association and category exemplar generation (e.g., Java, 1996; Light & Albertson, 1989; McEvoy et al., 1995; Mitchell & Bruss, 2003; Monti et al., 1996). Further, a large-scale study that used both perceptual and conceptual implicit tests reported a reliable age effect in perceptual but not conceptual priming (Small et al., 1995). Thus, a distinction between tasks that largely depend on perceptual versus conceptual processes cannot explain the full range of discrepancies in the literature.

There is also evidence that the ability to produce or generate a response declines with age, while identification processes are relatively spared (e.g., Fleischman & Gabrieli, 1998).

This *production-identification* distinction leads to the prediction that implicit tasks that draw upon identification, such as perceptual identification, lexical decision, and category exemplar verification, will be associated with less of an age difference than tasks that involve production, such as word-fragment and word-stem completion, and category exemplar generation (Gabrieli et al., 1994). Indeed, age-invariant priming has often been reported on perceptual identification tasks, but not consistently on word-stem completion and word-fragment completion. Interestingly, Winocur et al. (1996) reported age invariant priming on a word-fragment completion task coupled with a reliable age difference on a word-stem completion task, and although both tasks are thought to draw upon production processes, it is possible that completion of fragments may depend partly on the identification of a pattern of letters (Fleischman & Gabrieli, 1998). However, the identification-production distinction cannot account for all of the discrepancies in the literature; some studies have reported intact priming in older adults on tests of category exemplar generation (Light & Albertson, 1989; Monti et al., 1996) and verb generation (Prull, 2004).

Another issue is that priming appears to be least affected by age on tasks that use a latency measure and most affected on tasks with an accuracy measure. This may at least partly be due to the fact that older individuals are slower to respond in general. That is, priming tasks with a latency measure typically compare average response times (RT) for studied and new test items (i.e., a priming score calculated as the mean RT for new items minus the mean RT for studied items), but if older adults have a disproportionately longer baseline response speed (i.e., for items that are new at test) than young adults, then this would magnify their priming score (e.g., Ostergaard, 1994). Tasks that emphasize speed of responding have many benefits, such as in the case of perceptual identification where the rigid goal may contribute towards greater measure reliability, but between-group differences in baseline response times have not always been accounted for. Priming may have therefore been exaggerated in older compared to young adults in many published studies, leading to erroneous conclusions of an absence of age differences. To overcome this issue, it is important to calculate priming scores in proportion to the individuals' baseline response speed (i.e., [RT new – RT studied] / RT new) (see Chapman, Chapman, Curran, & Miller, 1994; Hartley, 1993). A number of studies in the literature have adopted this approach, yet some have reported age-invariant priming (e.g., Mitchell & Bruss, 2003; Mitchell & Schmitt, 2006) while others have not (e.g., Ward et al., 2013a; Ward, 2018).

Participant characteristics

Participant age and general cognitive function have also varied considerably across studies. Participants aged 60-70 years (often referred to as young-old) frequently demonstrate a smaller priming deficit compared to participants over the age of 70 years (often referred to as old-old) (e.g., Maki, Zonderman, & Weingartner, 1999). The same is true of explicit memory decline, and this may be indicative of general and progressive deterioration of a single memory system with advancing age. However, it cannot be ruled out that reductions in priming in the very old are linked to the pathology of non-normal changes in memory. Alzheimer's disease (AD) is associated with substantially greater neural degeneration than normal aging, in addition to the characteristic amyloid plaques and neurofibrillary tangles, which affect neocortical regions as well as structures within the medial temporal lobe (e.g., Brun & England, 1981). These features are linked to the rapid decline of explicit memory and in many cases have been shown to also affect implicit memory (e.g., Carlesimo & Oscar-Berman, 1992; Fleischman, 2007; Fleischman & Gabrieli, 1998; Meiran & Jelicic, 1995; Mitchell & Schmitt, 2006; Spaan, Raaijmakers, & Jonker, 2003). Thus, even if implicit memory is spared in normal aging, this may not be the case in dementia, and the inclusion of non-normal participants in normal aging studies muddies conclusions about the effect of normal aging on implicit memory. Ideally, an appropriate neuropsychological evaluation should be given to participants in normal aging studies, with specific criteria for the exclusion of participants with probable AD. Although the studies reviewed herein were reportedly based on samples of healthy older participants, in many cases the cognitive characteristics of participants were not formally established and neither was cognitive impairment ruled out.

It is also noteworthy that in many normal aging studies the participants were not what we would consider healthy older adults. Some participants had mild cognitive impairment (MCI), meaning that they suffer with minor problems in various cognitive abilities and are at a heightened risk of developing AD (e.g., Bennett et al., 2002). These individuals, who may show scores on the lower end of normal on standard neuropsychological tests such as the Mini Mental State Exam (MMSE, Folstein, Folstein, & McHugh, 1975) (e.g., a score in the region of 24-25 out of a possible 30), may be in a transitional phase between normal aging and AD (Sliwinski, Lipton, Buschke, & Stewart, 1996). Failure to exclude such participants may decrease the mean priming score of the group, making it appear impaired in respect to a young comparison group. Indeed, Davis et al. (1990) found a significant age effect on a word-stem completion task only in participants over the age of 70 years, and Winocur et al. (1996) found an age effect on a word-stem completion task for institutionalized, but not community-dwelling, older participants, yet it is conceivable that the former may not be representative of a healthy population.

Lastly, as well as potential differences in the cognitive status of participants between studies, performance on implicit tests may have also varied according to differences in factors such as pre-morbid intelligence, education level, vision, and physical health, all of which are known to correlate with memory (e.g., Christenson & Birrell, 1991). Thus, as well as ensuring that normal aging studies are based only on healthy older adults, it is essential that any reliable differences between groups of young and older adults in factors that may affect task performance are treated as covariates during analysis so that their contribution to the effect of interest can be partialled out. As this has seldom been accomplished in published studies, one cannot confidently assert that age effects in priming are due to a decline in implicit memory and not to a range of other factors.

Explicit contamination

In some situations, performance on implicit memory tasks may be contaminated by the use of explicit memory strategies. This is a significant issue when it comes to cognitive aging; given the well-established explicit memory decline with age, could reduced priming in older compared to young adults on an implicit test reflect the use of an explicit, intentional strategy that is more beneficial to young adults? Importantly, the meta-analysis by La Voie and Light (1994), that uncovered a significant effect of age on implicit memory, did not take explicit contamination into account, and Mitchell (1995) reported that age differences in implicit memory disappeared when the data were adjusted for explicit contamination (see also Mitchell & Bruss, 2003; Wegesin et al., 2004).

It is important to establish the conditions under which participants are likely to engage in an explicit strategy while performing an implicit test, and strive to employ implicit tests that are unaffected by such contamination. A necessary condition for the use of an explicit strategy is what has been termed *test awareness*. This refers to the spontaneous realization by participants while performing an implicit task that some items were presented in a prior phase or phases of the experiment. This realization may lead participants to adopt an explicit processing strategy in order either to increase speed or accuracy or to conform with perceived task demands. For instance, in the case of word-stem completion, although no reference is made to the earlier study phase and participants are instructed to complete each stem with the first word that comes to mind, if they become test-aware then they may instead attempt to explicitly recall items from the earlier experimental phase/s for use as solutions.

Such a strategy would be likely to result in impaired performance in older compared to young individuals, given their reduced explicit memory. Indeed, Russo and Parkin (1993) found an age effect in priming on a fragmented picture completion task, but the effect disappeared when explicit memory was equated between groups by giving young adults a second simultaneous task during the study phase. Thus, when the potential benefit of using an explicit processing strategy during the implicit task was equivalent in young and older adults, there was no reliable age difference in priming. Moreover, Geraci and Barnhardt (2010) found greater levels of test awareness and priming in young relative to older adults on word-stem completion and category production tasks, and a greater relationship between the two, and Park and Shaw (1992) reported identical scores on a word-stem completion task for young and older adults who did not report test awareness.

To directly examine the impact of test awareness on priming, some studies have compared the performance of groups of participants who are informed that previously studied items are present at test (aware participants) versus participants who are not informed (unaware participants), but results have been mixed. Brown, Nesblett, Jones, and Mitchell (1991) found no difference in priming on picture and word naming tasks between participants who witnessed previously studied and new item trials in separate blocks at test and were informed which block contained which type of item, versus those who were uninformed and witnessed interspersed studied and new trials within the test (see also Mitchell & Bruss, 2003, Experiment 2). The opportunity for explicit processing should be greater in informed (aware) participants, but unfortunately it was not monitored whether participants in the uninformed group spontaneously became aware. Bowers and Schacter (1990) found no difference in priming between informed and uninformed young participants on a word-stem completion task, but priming was greater in uninformed participants who spontaneously became test aware relative to those who did not (Experiment 1). In contrast, Mace (2003) reported enhanced priming in informed relative to uninformed young participants for items studied under semantic but not nonsemantic conditions.

MacLeod (2008) reviewed a range of measures to circumvent possible explicit contamination in implicit tasks, which typically involve reducing test awareness by disguising the purpose of the test, presenting test items very briefly, and using speeded responding. The effectiveness of such measures is difficult to appraise because test awareness has usually been evaluated post hoc using self-report questionnaires, which may have limited validity given the nature of self-report (e.g., Reingold & Toth, 1996; but see Barnhardt & Geraci, 2008). Participants often have poor insight into their own mental state and may not accurately report the level of awareness that they experienced during the test. For example, if a participant becomes aware in hindsight but nevertheless reports awareness on a post-test questionnaire, they may be excluded or wrongly grouped with ‘aware’ participants, even though they were not aware while completing the task. On the other hand, if a participant fails to report awareness on a post-test questionnaire due to demand characteristics then they may erroneously be labelled as ‘unaware’.

Another method of concealing the fact that previously studied items are present in an implicit test is to include a lower proportion of previously studied relative to new items (see Jacoby, 1983; Richardson-Klavehn, Lee, Joubran, & Bjork, 1994; Ward et al., 2013a). When there is a low ratio of previously studied to new trials, participants are less likely to notice the connection between the study and test phases. A handful of prior studies have used this method, usually to bolster an instructional manipulation (i.e., informed participants are exposed to a high proportion of studied trials and uninformed participants are exposed to a low proportion of studied trials). Jacoby (1983) reported enhanced priming on a word naming task in informed participants who witnessed 90% previously studied trials at test relative to uninformed participants who were exposed to 10% previously studied trials. However, Ward et al. (2013a) found no such difference.

A valuable method of studying the relationship between explicit and implicit memory is to measure the two concurrently on each test trial, such as in the continuous identification with recognition (CID-R) task (e.g., Stark & McClelland, 2000). This task involves the trial-by-trial capture of perceptual identification and recognition (Figure 1), and as will be discussed in the section on *Theoretical implications*, an age-related dissociation produced under these conditions would constitute compelling evidence that implicit memory is spared despite a reduction in explicit memory. However, as the implicit task in this paradigm is not performed under standard implicit instructions, it is important to consider the potential impact this has upon the priming measure. Does test awareness affect performance in the identification task? Brown, Jones, and Mitchell (1996) found that priming levels did not differ when identification and recognition judgements were presented concurrently on every trial relative to separate experimental phases. However, test awareness was not measured in the latter group. Ward et al. (2013a) reported a significant age effect in priming on the CID-R task, and rigorously examined the potential contribution of explicit contamination. Priming did not significantly differ in young participants when the identification task was presented alone under standard implicit instructions (and participants were monitored for spontaneous test-awareness) versus when concurrent recognition judgements were elicited (CID-R), nor was it affected by providing participants with optimal or adverse information for explicit processing: identification was not aided by telling participants whether the next item to be presented was previously studied or new, and was not worsened when incorrect cues were provided.

Thus, there is strong evidence that perceptual identification is immune to explicit contamination, and that there is a small but genuine age-related decline in priming on this task. It has been suggested that explicit processing is unlikely to occur on tasks such as this that require a speeded response, because identification is usually accomplished too quickly for the engagement of an explicit strategy (MacLeod, 2008). This is not to say that participants do not experience test awareness on such a task, merely that it does not affect the priming outcome. However, other implicit tasks may be susceptible to the effects of explicit contamination. This appears to be an issue on tasks such as word-stem completion, where the use of an explicit strategy has the clear potential to improve performance. Because spontaneous awareness occurs in many participants even when the purpose of the test is disguised (and may be more likely to occur in young than older participants), it is strongly recommended that explicit contamination be rigorously monitored in future studies.

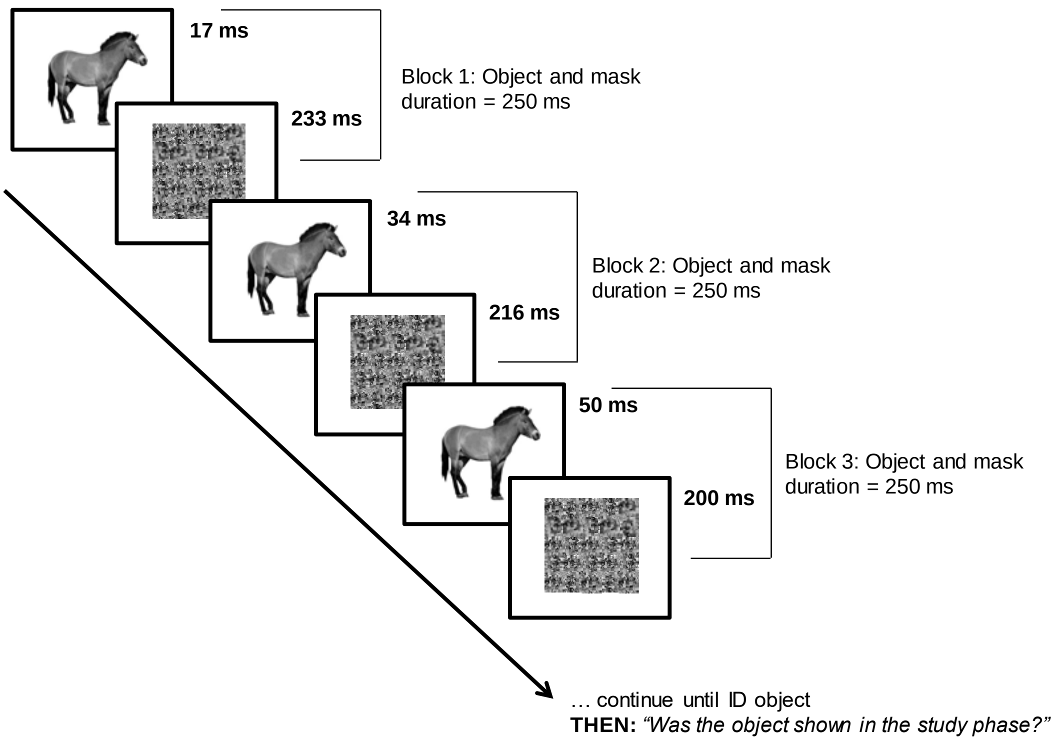

Figure 1. Example of a single trial in the continuous identification with recognition (CID-R) task in Ward et al. (2013a). An object, either seen in a previous study phase or new, gradually

clarifies from a background mask over time and participants must identify it as quickly as possible. Identification response time is captured upon keypress (priming measure) at which point the object disappears and the participant is prompted to type its name into a box. Immediately after, the object is shown again and participants are prompted to make a studied (old)/unstudied (new) recognition judgement (explicit memory measure).

Other factors

A range of other factors may interact with age to influence effects on implicit memory tasks. First, the time of day at which testing takes may seem inconsequential, but a growing body of evidence suggests that this may differentially affect priming outcomes in young and older adults. Young adults tend to show optimal task performance in the afternoon/evening, while older adults show optimal performance in the morning (e.g., Ngo, Biss, & Hasher, 2018), and it has been suggested that there are larger age differences in priming when testing takes place in the afternoon and young but not older adults are at their peak (see Amer, Campbell, & Hasher, 2016). To our knowledge the only comprehensive study looking at age effects on a range of implicit tasks in which participants were tested at their optimal time of day is that of Mitchell and Bruss (2003).

Another factor is the depth of encoding of the information that will later be tested. In some studies items presented at study are deeply encoded as participants are asked to make a semantic judgement in relation to them, such as an object categorisation, whereas in other studies encoding has been shallow as participants have simply been asked to engage with the perceptual features of presented items, such as their size or orientation. Due to a deterioration in conceptual processes and sparing of perceptual processes with age (see *Processing and task characteristics* section), older adults may be less able to engage in elaborative encoding, meaning that age effects may be more pronounced under semantic encoding conditions, while there may be less of an age difference under perceptual/shallow encoding conditions. There may be further interactions with the processing requirements at test: performance is typically greatest when there is an overlap in processing requirements at study and test, such as in a perceptual study phase followed by a perceptual priming task rather than a conceptual one (transfer appropriate processing, Morris, Bransford, & Franks, 1977; Roediger, Weldon, & Challis, 1989).

Finally, in some cases in the literature, target items have been presented in an unattended stream or as irrelevant information, to reduce explicit memory and disguise the true purpose of the study as much as possible. This has in some cases led to even greater implicit memory in older than young adults, which, coupled with weaker explicit memory for this information, constitutes a compelling double dissociation. For example, in Gopie, Craik, and Hasher (2011), participants judged the text colour of words and random letter strings in an initial study phase (the words themselves were task irrelevant), before completing a word-fragment completion task with either implicit instructions to complete fragments with the first word that came to mind, or explicit instructions to complete fragments with words from the previous phase. Completion of fragments with words from the previous phase was reliably greater in young than older adults in the explicit condition, and vice versa in the implicit condition. This pattern, however, was not replicated by Ward (2018), where an identical study phase was followed by the CID-R task outlined earlier. These discrepancies further highlight the important impact that the processing characteristics of the implicit task have upon age effects in priming. Future studies should attempt to provide further evidence that explicit and implicit memory can be doubly dissociated in aging, as such as observation would constitute the most compelling evidence for the selective preservation of implicit memory with age.

Aging and Implicit Learning

Repetition priming effects represent only one kind of implicit memory. It has been suggested that implicit memory encompasses a variety of learning and memory phenomena, such as classical conditioning, skill learning, and priming (e.g., Light & Burke, 1988; Schacter, 1987; Squire, 1986). Although it is beyond the scope of this review to provide a detailed summary of cognitive aging effects in all of these domains, it is valuable to consider key strands of evidence gained from tests of implicit learning. This, too, yields findings that defy a simple summary (see Prull, Gabrieli, & Bunge, 2000, for a thorough review).

Skill learning manifests in the form of improved performance across repetitions, such as faster speed or increased accuracy of a particular action. It is argued to be an implicit phenomenon that does not depend upon explicit memory, as early reports suggested that this ability is retained in individuals with amnesia (e.g., Corkin, 1968; Gabrieli, Corkin, Mickel, & Growdon, 1993; Milner, 1962; Nissen & Bullemer, 1987). Evidence from normal aging, however, is mixed. Some studies reported age differences favouring young adults on the development of a rotary pursuit skill, in which a small revolving target is tracked with a hand-held stylus more accurately across trials (Ruch, 1934; Wright & Payne, 1985). However, other studies reported no such age difference (e.g., Durkin, Prescott, Furchtgott, Cantor, & Powell, 1995). Age differences have also been reported in the acquisition of a mirror tracing skill, in which a geometric pattern is traced while viewed through a mirror (Ruch, 1934; Snoddy, 1926; Wright & Payne, 1985), as well as inverted word reading (Hashtroudi, Chrosnia, & Swartz, 1991), but in contrast other studies have reported no deficit in older adults' acquisition of a mirror reading skill (Durkin et al., 1995; Schugens, Daum, Spindler, & Birbaumer, 1997). Moreover, some studies suggest that older adults can learn a repeating sequence of key presses in serial reaction time tasks at the same rate as young adults (Howard & Howard, 1989, 1992; Knopman & Nissen, 1987; Nissen & Bullemer, 1987), but other studies suggest that they do not (e.g., Frensch & Miner, 1994, Cherry & Stadler, 1995, Curran, 1997, Howard & Howard, 1997; Howard, Howard, Dennis, & Yancovich, 2004; Jackson & Jackson, 1992).

Another example of implicit learning is learning of the spatial and/or temporal relationship between items or events. The spatial contextual cuing task (e.g., Chun & Jiang, 1998) is a commonly used task in this domain. In this paradigm, participants are required to detect a target letter (e.g., T) in a display containing a number of distracter letters (e.g., L's), where the location of the target and configuration of surrounding distractors is repeated across a number of displays. Normal participants show a gradual increase in target search speed for repeated displays, and it has been argued that this learning of the configurations takes place outside of awareness as participants do not need to make a particular effort to learn and are unable to explicitly state what they have learned (e.g., Barnes et al. 2008; Chun & Jiang, 1998; Chun & Phelps, 1999; Howard et al., 2004; but see Brockmole & Henderson, 2006; Endo & Takeda, 2005; Ono, Kauahara, & Jiang, 2005; Olson & Jiang, 2004; Preston & Gabrieli, 2008; Shanks, 2005; Vaidya, Huger, Howard, & Howard, 2007). If implicit memory is spared in normal aging then contextual cueing should be equivalent in young and older adults. Indeed, Howard et al. (2004) concluded that there is no age effect based on a comparison of the performance of young and older adults. However, although there was no statistical interaction of learning with age, the older group developed contextual cuing later than the young group. The interpretation of preserved contextual cueing in aging is therefore open to the same criticism as a host of other studies in the cognitive aging literature – there may have been insufficient power to detect a true age difference. Smyth and Shanks (2011) provided evidence of a reliable decline in contextual cuing with age, and moreover, experimentally matching visual search times in young and older adults did not alter the finding, suggesting that the effect cannot be accounted for by slower overall responding in older adults.

The range of issues reviewed in this chapter that may explain discrepancies in the implicit memory literature also apply to the tasks described here. For instance, the particular processing characteristics of the task used to examine skill learning may play a fundamental role in the emergence of age differences. Moreover, it is likely that many of these tasks did not have adequate reliability levels. In fact, Salthouse et al. (1999) suggested that the serial reaction time task is the only implicit learning task that has adequate reliability to detect age differences, and indeed Howard et al. (2004) reported that older adults showed reduced learning compared to young adults on this task. In the same article the authors reported equivalent contextual cuing in young and older adults, but as described above the null age difference does not constitute strong empirical support for spared implicit learning with age, and a reliable reduction was reported by Smyth and Shanks (2011). As such, at present there is little compelling evidence that implicit learning is spared with age.

Neuroscientific evidence

In evaluating the preservation versus decline of implicit memory with age, it is important to consider evidence that this form of memory is neurally distinct from explicit memory (e.g., Buchmer, 2004; Nyberg et al., 2004). If different brain regions are involved in or responsible for explicit and implicit memory function (discussed in Voss & Paller, 2008), and are susceptible to differential age-related decline, this may broadly explain age-related dissociations on explicit and implicit memory tests. As with the implicit learning literature, it is beyond the scope of this article to provide a full review of the vast neuroscientific evidence, but it is important to highlight key strands.

As has been discussed, age-related decline specifically in explicit memory has been linked to structural changes in the medial temporal lobe, particularly the hippocampus and entorhinal cortex (e.g., Geinisman et al., 1995; Kordower et al., 2001; Raz et al., 2004; Small et al., 2000; Stoub et al., 2005), and moreover individuals with amnesia due to damage to these regions often show a specific impairment to explicit memory (e.g., Conroy, Hopkins, & Squire, 2005; Graf et al., 1984; Hamman & Squire, 1997a; 1997b; Jacoby & Witherspoon, 1982; Stark & Squire, 2000; Warrington & Weiskrantz, 1970; 1974). This may suggest that while the hippocampus and medial temporal lobe are crucial for explicit memory, implicit memory may not be dependent on these regions. It has been argued that structures within the neocortex play a key role in implicit memory. For example, Gabrieli, Fleischman, Keane, Reminger, and Morrell (1995) reported a case in which an individual with damage to the right occipital lobe exhibited impaired priming and intact explicit memory. Consistent with these findings, a number of neuroimaging studies suggest that priming and recognition are associated with different patterns of neural activity. For example, there is evidence that explicit memory is associated with increased haemodynamic responses in prefrontal, parietal, and medial temporal regions (Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Schacter et al., 1996; Schott et al., 2005), while priming is associated with reduced responses in occipital, temporal, and pre-frontal areas (Henson, 2003; Schacter, Alpert, Savage, Rauch, & Albert, 1996; Schott, et al., 2005).

A recent large-scale study by Henson et al. (2016) provided evidence that three memory factors, namely associative and item memory (explicit) and visual priming (implicit), are differentially sensitive to age and supported by distinct brain regions. This study was based on over 300 participants between the ages of 18 and 88 years, and structural equation modelling (SEM) was used to relate memory effects to differences in grey and white-matter volume from magnetic resonance images. Behavioural measures of associative memory, item memory, and priming for each test item were indexed within a single trial, ruling out potential issues with taking separate samples of memory in different experimental phases (this point is discussed in the *Theoretical implications* section). Specifically, after studying everyday objects superimposed on positive, negative, or neutral background scenes, participants were asked to name a visually-degraded object (priming measure), judge whether it had been shown in the previous phase (item memory measure), and finally judge whether it had previously been paired with a positive, neutral or negative background (associative memory measure).

The authors reported reductions in associative and item memory with age, even after adjusting for individual differences in education and fluid intelligence, coupled with no decline in priming. Six regions of interest showed age-related grey- or white-matter volume reductions: The hippocampus, parahippocampus and fusiform cortex (grey), and the fornix, uncinate fasciculus and inferior longitudinal fasciculus (white matter). SEM modelling also revealed differential contributions of these brain regions to the memory factors. For example, hippocampal volume made a unique, positive, statistically-significant contribution to associative but not item memory or priming, while fusiform volume was associated with item but not associative memory or priming. Henson et al. (2016) provided some evidence that these regions are differentially involved in the effects (or non-effects) of age on distinct forms of memory, but much additional work will be needed to confirm this suggestion. The regions did not fully account for age effects as adding age to the structural equation model improved its fit, and of course caution should be applied given the null age effect in priming. Moreover, as Henson et al. themselves acknowledged, just because one association (e.g., between hippocampal volume and associative memory) is significant and another is not (e.g., hippocampal volume and priming), it does not follow that the associations themselves are significantly different. Nevertheless, this study provides intriguing support that implicit memory remains stable with age in the face of explicit memory decline, and that this is driven by distinct neural memory systems.

It is important to note, however, that not all studies have provided evidence that favours the conclusion that distinct brain regions are involved in explicit and implicit memory (reviewed in Dew & Cabeza, 2011). For example, Schott et al. (2005) found decreased activity in the hippocampus/medial temporal lobe for primed items, which goes against the view that priming is not dependent on this region. Other studies have also provided evidence that the medial temporal lobe is involved in priming (Jernigan, Ostergaard, & Fennema-Notestine, 2001; Ostergaard & Jernigan, 1993; Ostergaard, 1999; Turk-Browne, Yi, & Chun, 2006), and some functional imaging studies have indicated overlap in the regions involved in performance on explicit and implicit tasks (e.g., Henson & Gagnepain, 2010; Jernigan & Ostergaard 1993; Zust et al., 2015). Moreover, individuals with amnesia due to damage to this region do not always show spared priming (e.g., Chun & Phelps, 1999; Squire, Shimamura, & Graf, 1987).

Implications and future directions

Is implicit memory spared in normal aging? Unfortunately, there is no straightforward and unambiguous answer to this important question at present. Over the years it has come to be widely accepted that implicit memory is spared with age, but based on the large volume of discrepancies in the literature and the issues reviewed above, the validity of this conclusion is questionable. As has been discussed, the view that implicit memory is unaffected by aging has largely been based on studies that may have been underpowered, were associated with large numerical age differences, and/or used implicit tasks with poor reliability. Other studies based on larger samples and reliable tests have uncovered significant age effects in implicit memory, and meta-analyses suggest that there is a small but significant reduction in implicit memory with age (e.g., La Voie & Light, 1994). However, it is possible that this reduction is due to contamination of implicit task performance by explicit memory strategies, and/or the inclusion of older participants with early dementia or mild cognitive impairment. Various other task, processing, and methodological differences between studies may have contributed towards differential outcomes, making a clear conclusion very challenging to extract.

Given the notable implications surrounding this topic, reviewed below, further research is crucial. Future studies should aim to overcome the issues reviewed in this chapter, in an attempt to yield data from which clear conclusions can be drawn. At present there is no strong evidence that implicit memory is spared with age, so a fundamental goal for future studies is to attempt to provide such evidence. Cross-sectional studies should be highly powered and based on comparable samples of healthy young and older participants, who are rigorously screened for dementia and cognitive impairment. Both cross-sectional and longitudinal studies should employ reliable implicit tasks that are unaffected by explicit contamination or the use of different strategies. Under these conditions, robust evidence for preserved implicit memory would comprise completely stable priming in older adults over time, and/or completely equivalent priming in young and older adults, coupled with a reliable age difference in explicit memory. That is, rather than simply demonstrating that priming in young and older adults is not statistically different, in order to conclude that implicit memory is preserved with age it needs to be completely equivalent in the two age groups (supported for example by Bayesian analyses providing evidence in favour of the null hypothesis), or even greater in older than young adults. Indeed, the most compelling evidence for preserved implicit memory with age would be a double dissociation in which under appropriate circumstances priming is significantly greater in older than young adults despite significantly weaker explicit memory.

Practical implications

Even if implicit memory is not spared with age, the decline appears to be much smaller than that observed for explicit memory. As well as concluding on the basis of their meta-analysis that there is a significant decline in priming with age, La Voie and Light (1994) showed that the effect was smaller than that obtained from 36 effect sizes from explicit tests. There may therefore be practical ways in which implicit memory strategies could be utilized to compensate for the greater decline in explicit learning and memory. Older adults are particularly impaired in self-initiated processing and the ability to explicitly learn and recall associative links between separate units of information, which may negatively impact several real-life demands such as acquiring new face-name pairs or learning medication routines. The use of implicit strategies may be beneficial for such tasks, given evidence that older adults may be able to draw upon intact implicit processes to successfully bind separate units of information, and that these associations provide a boost to item memory (e.g., Craik & Schloerscheidt, 2011; but see Ward et al., 2016).

Moreover, if implicit memory is preserved in healthy aging but not in Alzheimer's disease and mild cognitive impairment (see Fleischman, 2007, for a review), or is reduced to a greater extent in non-normal aging, then suitably designed implicit tasks might provide a valuable early diagnostic tool. Explicit memory decline is a key feature of aging, but is not necessarily indicative of a progression to Alzheimer's disease (e.g., Chetelat et al., 2003; Marquis et al., 2002; Palmer et al., 2002). Explicit memory tests therefore have limited predictive validity when it comes to distinguishing between individuals who will transition from normal to non-normal aging. Suitable implicit tests, however, may be of considerable use. It may also be useful to link performance on implicit memory tests to known risk-factors for developing Alzheimer's disease, such as the ability to perform daily activities, as reduced priming may provide an early indicator that an individual is at risk. On the whole, the use of implicit tasks and strategies may offer significant opportunities for extending the functional independence of an aging population.

Theoretical implications: The structure of human long-term memory

The preservation versus stability of implicit memory with age holds significant theoretical implications for how we understand the organisation of human long-term memory. A functional distinction has been drawn between explicit and implicit forms of memory (e.g., Gabrieli, 1998; 1999; Schacter, 1987; Schacter & Tulving, 1994; Squire, 1994, 2004, 2007, 2009; Tulving & Schacter, 1990), and Squire has argued that the systems "*can be distinguished in terms of the kinds of information they process, the principles by which they operate, and the brain structures and connections that support them*" (Squire, 2007, p. 343). It is assumed that the explicit system is responsible for the conscious retrieval of previously learned information, while the implicit system underlies classical conditioning, implicit learning, and repetition priming effects. The particular dissociation between explicit and implicit memory often reported in the normal aging literature has been taken as a key strand of evidence for this multiple-systems view (e.g., Mitchell, 1989; Mitchell, Brown, & Murphy, 1990). The argument is that selective deficit to explicit memory function with age, coupled with preserved implicit memory, is an expected observation if the two are driven by independent systems.

As has been discussed, the dissociation of explicit and implicit memory in normal aging is similar to that seen in individuals with amnesia due to damage to the hippocampus and medial temporal lobe (e.g., Conroy et al., 2005; Graf et al., 1984; Hamman & Squire, 1997a; 1997b; Jacoby & Witherspoon, 1982; Stark & Squire, 2000; Warrington & Weiskrantz, 1970; 1974). This, together with evidence from a range of neuroimaging studies (see *Neuroscientific evidence* section), may suggest that different brain regions are responsible for explicit and implicit memory function. While the hippocampus and medial temporal lobe appear to be crucial for explicit memory, the right occipital lobe may play a key role in implicit memory; Gabrieli et al. (1995) reported a case in which damage to this region resulted in impaired priming and spared explicit memory. However, as with the aging literature, there are published instances in which individuals with amnesia do not show spared implicit memory (Chun & Phelps, 1999; Squire et al., 1987), and some functional imaging studies have indicated overlap in the brain regions involved in the performance of explicit and implicit tasks (e.g., Jernigan & Ostergaard 1993; Schott et al., 2005).

It has been argued that single dissociations such as a significant age difference in explicit memory coupled with a nonsignificant difference in priming cannot constitute strong evidence for multiple memory systems, and an alternative view is that explicit and implicit memory are driven by a single system (e.g., Berry et al., 2006; 2008a; 2008b; Berry et al., 2012; Berry, Ward, & Shanks, 2017; Buchner & Wippich, 2000; Dunn, 2003; Nosofsky et al., 2012). As has been reviewed in this chapter, several studies and meta-analyses indicate that both explicit and implicit memory decline with age, and there are several reasons why age effects may sometimes go undetected on implicit tests. Another methodological issue that may contribute to differential effects on explicit and implicit tests is the fact that the two are usually presented in separate experimental phases. Scores may dissociate because there is a longer study-test delay for one task than the other, or because participants adopt different levels of motivation in the two tasks, especially as explicit tasks are generally more demanding than implicit tasks. These factors may also interact with aging to differentially affect outcomes on explicit and implicit tests. For samples of explicit and implicit memory to be as comparable as possible, they should be taken for the same items at around the same point in time.

A dissociation produced under these circumstances would constitute more compelling evidence for independent memory systems. Ward et al. (2013a) investigated the effect of aging on recognition and priming using the continuous identification with recognition (CID-R) task (Figure 1). Following an initial study phase, each CID-R trial involved the identification of a studied or new item (pictures of everyday objects) as it gradually clarified from a background mask (priming measure), followed immediately by a recognition judgement. For each test item, priming and recognition were therefore captured within a few hundred milliseconds of each other, and both were significantly lower in older relative to young adults.

The CID-R paradigm also allows certain predictions that are inherent in the multiple-systems account to be tested, for example, that performance on a priming task (e.g., perceptual identification) is unrelated to performance on a recognition task. Under the multiple-systems view one would expect equivalent identification latencies for studied items regardless of whether or not they are recognized (i.e., equivalent latencies for hits and misses). A dissociation at the item level when the priming task immediately precedes recognition constitutes strong support for independent systems – if the two are driven by the same system and measured at approximately the same point in time, differences should not occur. As such, a great many studies have examined the relationship between priming and recognition, but with specific relevance to cognitive aging, Mitchell et al. (1990) found that priming in picture naming did not significantly differ for studied items that were remembered versus those that were not in young and older adults. In contrast, Ward et al. (2013a) found that priming was significantly greater in both young and older adults for recognition hits versus misses. It is beyond the scope of this chapter to review the wider literature that has attempted to understand the relationship between priming and recognition, but it can be noted from decades of research that it is heavily disputed that there is a sharp distinction between the two (see e.g., Addante, 2015; Berry, Shanks, Speekenbrink, & Henson, 2012; Dew & Cabeza, 2011; Reder, Park, & Kieffaber, 2009; Shanks & Berry, 2012).

The application of computational models has offered further theoretical insight into the issue of the organisation of memory in recent years. Formal single-system models have successfully reproduced dissociations that on the surface appear to be indicative of multiple memory systems, suggesting that such observations are not incompatible with the single-system view, (e.g., Berry et al., 2006; Berry et al., 2008a; 2008b; Berry et al., 2012; Jamieson, Homles, & Mewhort, 2010; Kinder & Shanks 2001; 2003; Nosofsky et al. 2012; Shanks & Perruchet, 2002; Shanks, Wilkinson, & Channon, 2003). The model by Berry and colleagues assumes that a single memory signal drives performance on both explicit and implicit tasks, but that there are independent sources of random noise, with greater variance of noise in the implicit task. The model has reproduced dissociations between recognition and priming such as those seen in individuals with amnesia (e.g., Conroy et al., 2005), and also those seen in normal aging (e.g., Ward et al., 2013a). These dissociations are therefore not necessarily due to a selective deficit to an explicit memory system. Moreover, Berry et al. (2012) developed two multiple-systems models in which independent signals either make unique contributions to performance on explicit and implicit tests or have some degree of correlation, but model selection analyses indicated that the single-system model provided a better fit of the data from the amnesia and normal aging studies discussed above (see also Ward et al., 2013b).

On the whole, cognitive aging continues to provide a fruitful platform from which to investigate theoretical issues around the structure and organisation of human memory. However, age-related dissociations should not be used as a basis from which to postulate a sharp distinction between explicit and implicit memory phenomena. As has been discussed, such observations do not constitute sufficient or necessary evidence for the existence of multiple memory systems. Further advancement will be gained from rigorously controlled behavioural studies together with the application of single and multiple systems models to test specific predictions.

Conclusions

Although at present there is no clear answer to the question of whether implicit memory is spared with age, it is clear from this review that there is an absence of robust evidence from which to accept the traditional view that it is preserved. A growing body of studies and meta-analyses suggest that there is a decline in implicit memory with age, albeit smaller as compared to the decline in explicit memory. However, it remains to be seen whether this small reduction in priming with age represents a genuine decline in implicit memory. This rests crucially on eliminating the possibility that it reflects contamination of the priming measure by explicit processing and/or the inclusion of older participants with dementia or mild cognitive impairment.

Several recommendations for methodological improvement have been outlined, and a crucial goal for future research will be to attempt to provide solid evidence for the preservation of implicit memory with age. Future studies should be highly powered, with comparable samples of healthy young and older participants, who are rigorously screened for dementia and cognitive impairment, and use reliable implicit tasks that are unaffected by explicit contamination. Under these conditions, the most compelling evidence for preserved implicit memory in normal aging would be to observe completely equivalent priming in young and older adults, coupled with a reliable age difference in explicit memory, or a double dissociation in which priming is significantly greater in older than young adults despite significantly weaker explicit memory. Further insights are likely to involve a combination of rigorous behavioural methods, computational modelling, and functional imaging.

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